



Shi, Y., Hallett, S. R., & Zhu, M. (2017). Energy Harvesting behaviour for Aircraft Composites Structures using Macro-Fibre Composite: Part I – Integration and Experiment. *Composite Structures*, 160, 1279–1286. <https://doi.org/10.1016/j.compstruct.2016.11.037>

Peer reviewed version

License (if available):
CC BY-NC-ND

Link to published version (if available):
[10.1016/j.compstruct.2016.11.037](https://doi.org/10.1016/j.compstruct.2016.11.037)

[Link to publication record in Explore Bristol Research](#)
PDF-document

This is the accepted author manuscript (AAM). The final published version (version of record) is available online via Elsevier at <http://dx.doi.org/10.1016/j.compstruct.2016.11.037>. Please refer to any applicable terms of use of the publisher.

University of Bristol - Explore Bristol Research

General rights

This document is made available in accordance with publisher policies. Please cite only the published version using the reference above. Full terms of use are available:
<http://www.bristol.ac.uk/red/research-policy/pure/user-guides/ebr-terms/>

Energy Harvesting behaviour for Aircraft Composites Structures using Macro-Fibre Composite: Part I – Integration and Experiment

¹*Yu Shi, ³Stephen R. Hallett, ²Meiling Zhu

¹Mechanical Engineering, University of Chester, Pool Lane, Chester, CH2 4NU, UK.

²College of Engineering, Mathematics and Physical Sciences
University of Exeter, Exeter, EX4 4QF, UK.

³Advanced composite centre for innovation and science (ACCIS),
University of Bristol, Queens building, University Walk, Bristol, BS8 1TR, UK.

*y.shi @chester.ac.uk

Abstract: This paper investigates new ways to integrate piezoelectric energy harvesting elements onto carbon-fibre composite structures, using a new bonding technique with a vacuum bag system and co-curing process, for fabrication onto airframe structures. Dynamic mechanical vibration tests were performed to characterise the energy harvested by the various integration methods across a range of different vibration frequencies and applied mechanical input loadings. An analytical model was also introduced to predict the power harvested under the mechanical vibrations as a benchmark to evaluate the proposed methods. The developed co-curing showed a high efficiency for energy harvesting at a range of low frequencies, where the co-curing method offered a maximum improvement of 14.3% compared to the mechanical bonding approach at a frequency of 10Hz. Furthermore, co-curing exhibited potential at high frequency by performing the sweep test between frequencies of 1-100 Hz. Therefore, this research work offers potential integration technology for energy harvesting in complicated airframe structures in aerospace applications, to obtain the power required for environmental or structural health monitoring.

Keywords: energy harvesting, macro fibre composite, carbon fibre composite, bonding, co-curing

1. Introduction

For the aircraft industry, significant interest has been generated in the use of wireless sensing technology to perform structural health monitoring of critical airframe structures such as wings or fuselages. To supply the power source for wireless sensor communication nodes (WSCNs) the batteries are externally mounted onto the aircraft structure as the most common solution. However, the capacity of batteries is limited and they need to be replaced periodically, with the resulting maintenance inducing additional costs. Moreover, the extra weight of batteries could impact aircraft design so that it will weaken flight performance and result in unexpected

cost and environmental issues. Therefore, energy harvesting technology has paid more attention to power wireless sensing for structural health monitoring in the aircraft industry. Many studies have been reported to investigate energy harvesting for aircraft applications [1-9]. MicroStrain developed a whole system of energy harvesting- powering wireless pitch link and successfully tested energy harvesting during flight to power wireless strain sensors for direct load monitoring of Bell helicopter rotating pitch link [1-2]. They used epoxy to bond the energy harvesting elements named macro-fibre composite (MFC) directly onto the pitch link while a strain gauge was also attached to record the pitch link loads. Chiarelli et al. [3] attached energy harvesting elements by direct bonding at the end of a wing with an active flap. Churchill et al. integrated energy harvesting elements onto a composite beam with a vibration of frequency between 60 to 180 Hz and peak-to-peak mechanical strain of 75 to 300 $\mu\epsilon$ applied, to demonstrate the capability of harvesting energy and powering a wireless sensor node using this energy [4]. Zhu et al. developed a low frequency strain energy harvesting system by integrating MFC onto the composite and aluminium substrate to demonstrate the efficiency of the energy harvester [5].

However, most research published has only used direct bonding of energy harvesting elements onto the measured structure using adhesive agents [1-4, 10-15] and has rarely discussed the improvement of energy harvesting efficiency by developing novel integration methods of energy harvesting elements. Exploring an efficient fabrication method and process for integration of piezoelectric energy harvesting elements onto carbon-fibre composite structures seems to be essential for energy harvesting technology toward aircraft applications. In particular, the experimental tests in the literature are standardly coupon-size material, and there are few methods introduced for more complicated components such as a curved airfoil that is commonly seen for airframe applications as direct bonding is not well suited for complicated and curved airframe structures.

Therefore, in this paper novel integration methods are developed to improve the capacity of energy harvesting, compatible with curved aircraft structures, for carbon fibre/epoxy composites that will be fabricated, as well as for existing composite structures. The energy harvesting elements were laid up with the carbon fibre/epoxy prepreg at the fabrication stage and co-cured within an autoclave, while direct bonding by adhesive within a vacuum bag was also developed and compared. The integration approaches proposed were characterised under different mechanical load conditions from low (1Hz) to high (100Hz) frequencies. An

analytical model was also introduced to predict the power harvested, in order to assess the various integration methods.

2. Selection of energy harvesting elements and integration methods

2.1 Selection of energy harvesting elements

Traditional piezoelectric materials (PZT) have been extensively used in the fields of energy harvesting. However, the ceramic property of the monolithic piezoelectric material is very brittle, which makes them vulnerable to accidental breakage during handling and bonding procedures. It is therefore difficult to apply them to curved surfaces when working with very flexible or lightweight structures [16, 17]. In this work, two selection criteria are necessary for application to aircraft: 1) ability to work under a harsh environment due to low temperatures during flight; 2) suitability for streamlined airframe structures. Macro-fibre composite (MFC) developed by NASA Langley Research Centre [18] has features of flexibility to allow their application to curved surface due to a polymer shell [19] and have been successfully applied to the space shuttle missions, where working temperatures range from -100 to 260 °C [20]. Therefore, macro-fibre composite (MFC) is an ideal candidate for application of energy harvesting for aircraft structure.

In general, MFC can be categorised into two types i) the electric field couples between neighboured finger electrodes of different polarity in the fiber direction (d33 effect, denoted by MFC P1 type) using non-metalised PZT (see Fig. 1 (left)); ii) a contracting MFC uses PZT fibers integrated with top and bottom electrodes by dicing metalised PZT wafers (d31 effect, denoted by MFC P2 type) where finger electrodes of each side can be connected together and the applied electric field is thus applied through the fibre thickness. The P2 type MFC has been developed with the advantage of reduced driving voltage of 360V and is particularly ideal for energy harvesting because of its higher capacitance and increased charge generation at the same strain level compared with P1 type MFC [20, 21]. Therefore, in this work MFC8528-P2 (d31 effect) with active area of 85mm x 28 mm was selected as the energy harvesting elements.

2.2 Exploration of integration method

In order to improve the efficiency of energy harvesting and feasibility onto complicated aircraft composite structure, two main standards were followed that 1) the proposed integration method can effectively reduce the thickness of adhesive with good control of uniformity; 2) the

proposed method is applicable to curved shape during integration process. As shown in Fig. 1, for integration of energy harvesting elements onto curved airframe, the most ideal way to match these two standards is to use vacuum bag to form flexible energy harvesting (EH) elements. An efficient way is during the fabrication process of composite structure the EH elements are placed onto the top of composite prepreg and cured together with composite laminate, so the inherent epoxy of composite prepreg can bond EH elements within vacuum bag, which is known as “co-curing”. This method avoids the use of additional adhesive for integration, so theoretically the energy harvested from external vibration can be completely transferred without extra energy consumption by adhesive layers. In addition, for consideration of existing composite structures, that co-curing would not be suitable for, the direct bonding using vacuum bag method was proposed, in which the thickness and uniformity of adhesive layer was controlled by the extra pressure applied during curing of adhesive epoxy within vacuum bag. Compared to the general mechanical bonding method, the vacuum bag can help energy harvesting elements flexibly integrate onto a curved shape and the appropriate pressure control can effectively improve the energy harvested with less consumption by adhesive epoxy. Therefore, these two approaches will be developed in this work and the specified process is briefly introduced below.

2.2.1 Co-curing

For co-curing process, first of all the composite prepreg was prepared for fabrication with size of 350mm x 320mm, which aerospace grade carbon fibre/epoxy prepreg IM6/950 (as shown step 1 in Fig. 2) was used in this work. Steel is selected for the support because steel is less sensitive to the high temperature of curing and therefore there is no unexpected bending induced, which was found when aluminium was used as support. The support plate is also covered by PTFE film to isolate the prepreg for release after curing. The composite was designed to lay up with stacking sequence of $[45_2/0_2/-45_2/90_2]_{2s}$, which is a typical generic quasi-isotropic layup. Once the lay-up has been done, an MFC energy harvesting element was placed onto the top of the first ply of the lay-up for co-curing, as shown by step 2 in Fig.2. In order to avoid the electrodes being sealed by the resin, tape was used to cover the four electrodes of the MFC for protection. In step 3 of Fig. 2, the composite lay-up with MFC placed on the top was sealed within a vacuum bag system. This step is the most important for the whole manufacturing, which could determine the overall quality of composite plates. The vacuum ports are placed on the free space of the support to connect with the vacuum pump. It

is necessary to keep the bag as flat as possible, without any wrinkles that could lead to a low surface quality of composite plate. Once the vacuum bag was checked for any leaks, it was placed into an autoclave, which is shown in step 4 of Fig. 2. Curing is performed based on the specific temperature and pressure programs recommended by the pre-preg manufacturer, which is 125° C with pressure of 90 psi for the IM6/950 used in this work. Finally, the cured composite structure with MFC is shown in step 5, Fig. 2. A high quality of integration can be found in that the MFC was perfectly embedded by the epoxy of prepreg on the top surface, while the electrodes were exposed to be connected with electric cables to a measurement device.

2.2.2 Directly bonding

Co-curing was proposed as it is ideal to effectively improve quality of integration for energy harvesting elements during the fabrication process. However, in reality the composite airframe could have been made in advance, so co-curing cannot be suitable anymore for integration. An adhesive has to be employed to bond the energy harvesting elements onto composite structure. The most common way is to bond energy harvesting elements onto the substrate under mechanical force, such as being fixed by clamps directly. It is easy to perform, but the mechanical load cannot be uniformly distributed onto the bonding area during curing. Moreover, the mechanical load value could be not high enough to squeeze the extra adhesive epoxy out so that a large amount of energy harvested from the external mechanical source could be dissipated by the adhesive layers. In order to minimise the effect of the adhesive layer on energy harvesting, the vacuum bag method was proposed in this work to apply an external pressure during curing. As shown in Fig. 3 (step 1), the MFC was initially place onto the upper surface of the composite substrate. It has to be mentioned that the surface of composite substrate was processed by sandpaper in advance, in order to obtain a better quality of bonding. Araldite 2014 was used in this work to bond the MFC onto the composite substrate and the whole system was then sealed within a vacuum bag. Under the recommendation data of curing from manufacturer, it was cured at 70°C for 3 hours with pressure of 60 psi [5] applied by autoclave. The composite substrate with MFC bonded is shown in Fig. 3 at step 3. It can be seen in Fig. 3 that adhesive epoxy near the edge of MFC can be found squeezed out by extra pressure applied during the curing process. As comparison, MFC was also bonded by mechanical bonding where a steel bar was stacked onto the top surface of the MFC integrated composite. G-clamps were used to hold the steel bar covering onto the MFC and composite substrate to help apply mechanical load during curing.

3. Experimental test

3.1 Dynamic mechanical loading

The 5mm thick composite laminate with MFC integrated was cut to 300mm long, 50 mm wide, ready for test. The mechanical vibration tests were performed by electrodynamic test instrument Instron E10000 under various mechanical loading applied. The composite substrate was subjected to the cyclic loading $F = F' + F_0 \sin(2\pi ft)$. The equivalent mechanical strain can be thus achieved for dynamic tests and measured directly by the extensometer, as shown in Fig. 4a. The preload F' was set to a positive value of 5kN so as to keep the composite substrate always in tension during tests. The peak-to-peak strain of 340 $\mu\epsilon$ and 500 $\mu\epsilon$ were used in reference to the reported in-flight strain range [5]. Excitation frequencies between 1 and 100 Hz [22-24], which are generally reproduced in a real flight data, were used in the experiment to identify the capacity of the energy harvesting under various frequencies.

3.2 Measurement of output power harvested

In order to measure the power harvested through mechanical loading input, MFC terminals were directly connected to the data acquisition system. The energy harvesting capacity was characterised by applying a varying resistive loading during tests through the external resistor connected, as shown in Fig. 4b. The voltage across the connected resistor can be measured by a LabVIEW interface and the power harvested was therefore calculated based on the measured voltage. The details of the theoretical derivation can be found in the following section for the analytical model. A range of electric load of 10-200 k Ω was performed to find the optimal value to achieve the maximum power harvested at different test frequencies.

4. Theoretical model for energy harvesting

The analytical prediction can effectively assess the capacity of energy harvesting by various integration approaches proposed in this work. To analytically predict the power harvested resulting from the external mechanical loading, the constitutive equations are introduced to develop the analytical model. Based on the linear piezoelectric theory [25], the mechanical stress and electric displacement field can be obtained:

$$\sigma = C\varepsilon + e^T E$$

$$D = \varepsilon_p E + e \varepsilon \quad (1)$$

where D is electrical displacement field and ε_p is the dielectric permittivity of MFC; E is the electric field; e is the coupling property where can be expressed by piezoelectric constants d and composite stiffness C ($e=d \times C$). σ and ε are the mechanical stress and strain applied, respectively.

In order to predict the power harvested when the dynamic tensile load applied (length direction of composite substrate in Fig. 4b), the electrical charge through the thickness can be calculated as a function of the strain applied in x direction and the electric field within the active area of MFC:

$$D_z = \varepsilon_p E_z + e \varepsilon_x \quad (2)$$

The charge generated within the MFC layer can be expressed by integrating the electric charge D_z on the active area of MFC:

$$Q = \int_A D_z dA = A(\varepsilon_p E_z + e \varepsilon_x) \quad (3)$$

where A is the active area of MFC that is $A = bL$; b and L are active width and length of MFC, respectively. The electric field E_z can be expressed as:

$$E_z = -\frac{\partial V}{\partial z} = -\frac{V}{t} \quad (4)$$

where V is the voltage generated and the t is the thickness of MFC layer.

The charge Q and current I are functions of the time and therefore the current amplitude can be obtained by the charge times the frequency [26]:

$$I = \omega Q = 2\pi f Q = \frac{V}{R} \quad (5)$$

where f is the frequency applied for mechanical vibration tests. Combining equations (1)-(4) and substituting into Eq (5), the amplitude of voltage can be expressed as:

$$V = \frac{et\varepsilon}{\varepsilon_{33}R + \frac{t}{2\pi f b L}} R \quad (6)$$

The averaged output power P harvested across the MFC can be thus calculated as:

$$P = \frac{|V|^2}{2R} \quad (7)$$

The detailed material properties of MFC used for analytical prediction are listed in Table 1 where the recommended data is mainly obtained from Smart Material [20, 27-28].

5. Results and discussions

5.1 Comparison of integration methods

As discussed above, two approaches have been proposed to integrate MFC into a composite structure, firstly one for during fabrication of the airframe and secondly one for existing composite aircraft structures. In order to find out which can offer most efficient energy harvesting, the power harvested by co-cured and directly bonded (vacuum bag method and mechanical bonding) were compared under dynamic mechanical tests subjected to consistent mechanical loading and frequency (10Hz).

Figure 5a shows power harvested for composite substrate with MFC integrated by different methods under peak-to-peak strain of $340\mu\epsilon$ at 10Hz. It can be seen in Fig. 5a that the power harvested is sensitive to the electric load applied, where the optimal power can be obtained at a resistance of $80\text{ k}\Omega$ for these three tests. Co-curing gives the highest power (1.6 mW) compared to the bonding approach, with the power harvested being 23% higher than mechanical bonding method. Similarly, in Fig. 5b a peak-to-peak strain of $500\mu\epsilon$ was applied and the optimal power harvested was measured by the co-cured sample. The maximum power harvested for co-curing reached 3.4 mW when subjected to the electrical load of $80\text{ k}\Omega$, which is 21.4% higher than that scavenged by the mechanical bonding sample. For both mechanical loadings, the co-cured sample consistently showed the highest power harvested compared to the other two methods. This was further verified by mechanical tests under different excitation frequencies and strain levels applied. In Fig. 6, the excitation frequencies of 20 Hz and 50 Hz were applied while the composite substrate was subjected to the mechanical strain of $340\mu\epsilon$ and $500\mu\epsilon$, respectively. The maximum power that can be harvested was always given by co-curing approach. The full set of test data for the different integration methods is shown in Table. 2 for the frequency range from 10 Hz to 50 Hz. Therefore, co-curing is identified as the optimal approach for integration of MFC. It should also be noted that although the maximum power

harvested by vacuum bag method was slightly lower than co-curing, it is still a good method for MFC integration to achieve efficient power harvesting for existing composite structures, when the co-curing might be difficult to perform.

In addition, the analytical model was developed to predict power harvested under strain levels of 340 $\mu\epsilon$ and 500 $\mu\epsilon$ at excitation frequency of 10 Hz. It is found the predicted power was always higher than the experimental tests. This is most likely to be due to the active area of energy harvesting elements being assumed to be uniformly distributed whereas in reality the piezoelectric fibres are stacked together, which eventually leads to underestimation. Therefore, the analytical model can further help verify the conclusion that co-curing is most efficient for energy harvesting due to the maximum tested power being closest to the predicted value, as shown in Fig. 5.

5.2 Effects of the applied strain and frequency

During flight the vibration strain and excitation frequency will be varied, so it is important to know the effect of mechanical input (vibration strain and frequency) on the capacity of energy harvesting. The co-curing was thus tested under both strain levels of 340 $\mu\epsilon$ and 500 $\mu\epsilon$ and frequencies ranged from 1 Hz to 100 Hz, since it has been recognised as the optimal method for integration of energy harvesting elements onto composite structure based on experimental results presented in section 5.1.

In Fig. 7 the maximum power harvested at each excitation frequency applied is shown. It can be seen that the maximum power harvested increases linearly with frequency for both tests under different vibration strain levels. It is worth noticing that the maximum power was obtained by the optimal electric load applied at individual frequency value, with the detailed value listed in Table.3. This is due to the impedance matching theory of energy harvesting elements, $|Z| = \frac{1}{\omega C}$, where the impedance is an inverse relationship with frequency. The maximum power was also successfully predicted by the analytical model, shown in Fig. 7. For both cases, the analytical prediction was higher due to the active area of energy harvesting elements being assumed to be fully solid. The analytical model also helped to determine the optimal electrical loading at the corresponding frequency before tests, which significantly improved the efficiency of experimental measurements. In Table. 3 it can be seen that at low frequencies (1-10 Hz) the power harvested by the test is close to the analytical prediction, however, the difference increases at higher frequencies. This could be due to more energy being

dissipated at higher frequency or the nonlinear behaviour of the energy harvesting material. Therefore, it is helpful to know the capacity of energy harvesting at low and high frequencies, respectively, based on the experimentally measured data, especially through the comparison with the analytical prediction. It has been found to complete a single transmission for environmental monitoring by an Unmanned Aerial Vehicle (UAV), the power consumption required is 22.37mW [5]. From Table.3 it can be seen that that this can be achieved when the excitation frequency is high enough (over 70Hz) and subjected to a vibration strain of 500 $\mu\epsilon$. For the application of low frequency, multi-energy harvesting elements can be integrated together to increase the power harvested to satisfy the requirement of transmission for this application.

6. Conclusions

In this paper, an efficient fabrication method and process to integrate piezoelectric energy harvesting (EH) elements onto carbon-fibre composite structures was developed. For airframe structures during fabrication co-curing was proposed to integrate EH elements together with carbon fibre/epoxy prepreg. This approach avoids the usage of additional adhesive and therefore effectively improves the efficiency of energy harvesting. Moreover, it is flexible enough to be integrated to a complicated structure at the fabrication stage. In addition, considering an existing structure that has been cured in advanced, a vacuum bag method was developed to offer a relatively thin and uniformly distributed bonding layer for direct bonding. Both methods were fabricated and tested compared to the common mechanical bonding method to find out the optimal method for energy harvesting.

Under various vibration strains and excitation frequencies applied, the co-curing always offers the highest power harvested compared to that measured by direct bonding methods. In particular, the improvement of power can reach 23% higher than mechanical bonding. The vacuum bag method for direct bonding generated harvested power slightly lower than co-curing, but it is still an efficient way to improve efficiency of energy harvesting and flexibly integrate onto complicated fabricated composite structures, for situations where co-curing might be difficult to perform. An analytical model was also developed to predict power scavenged at the same strain level and frequency as the experimental tests. Analytical predictions were always above the experimental measurements due to the assumption of the active area of the energy harvesting elements being fully solid rather than stacked fibres in

reality. The analytical results were also helpful to evaluate the various integration approaches, showing that co-curing was closest to the analytical prediction and therefore it is optimal for integration, with improved efficiency.

The effect of applied mechanical strain and frequency was studied in this work. The power harvested grew linearly with increasing frequencies for both applied mechanical strains. The maximum harvested power was measured by finding the optimal electric load in experiments for the varying frequency, which is due to the impedance matching theory of energy harvesting elements. The maximum harvested power was between 0.16 – 42.1 mW at a frequency range of 1 – 100 Hz and mechanical strain of 340 $\mu\epsilon$ and 500 $\mu\epsilon$. This is sufficient to activate a single transmission of a microcontroller that requires a power of 22.37 mW in total. Therefore, it has potential to be implemented into a system designed for powering wireless sensor nodes for environmental monitoring in a UAV.

Acknowledgements

The authors gratefully acknowledge the support of the Engineering and Physical Sciences Research Council (EPSRC: EP/K020331/1) for “En-ComE : Energy Harvesting Powered Wireless Monitoring Systems Based on Integrated Smart Composite Structures and Energy-Aware Architecture” supervised by Prof. M. Zhu.

Reference:

1. SW. Arms, CP. Townsend, JH. Galbreath, DL. Churchill, M. Augustin, D. Yeary, P. Darden, N. Phan. “Tracking pitch link dynamic loads with energy harvesting wireless sensors”. presented at the American Helicopter Society 63rd Annual Forum, Virginia Beach, VA, (2007).
2. SW. Arms, SM. Moon, N. Phan. “Energy harvesting wireless sensors for helicopter damage tracking”. Proceedings of AHS international forum 62, Phoenix, (2006).
3. MR. Chiarelli, A. Cozzolino, J. Kunzmann, L. Lanzi. “Wings of the future: feasibility of the integration of MFC into the primary structures of aircrafts and definition of control system requirements.” Future wings project. 7th framework programme aeronautics and air transport (AAT) , (2013).

4. DL. Churchill, MJ. Hamel, CP. Townsend, SW. Arms. "Strain energy harvesting for wireless sensor networks". *Proc. Smart Struct. Mater. Conf. Proc. SPIE* 5055, 319–27 (2003).
5. V. Marsic, A. Giuliano, M. Zhu. "Energy autonomous sensing systems based on integrated piezo-fibre composites with carbon-fibre laminates." CDE23681 final report, Cranfield University (2012).
6. MR. Pearson, MJ. Eaton, R. Pullin, CA. Featherston, KM. Holford. "Energy harvesting for aerospace structural health monitoring systems." *Modern practice in stress and vibration analysis. Journal of physics: Conference series* 382 (2012).
7. O. Sosnicki, N. Lhermet, F. Claeysen. "Vibration energy harvesting in aircraft using piezoelectric actuators." *Actuator 2006, 10th international conference on new actuators. Germany* (2006).
8. D. Zhu, SP. Beeby, MJ. Tudor, NR. Harris. "A credit card sized self-powered smart sensor node." *Sens. Actuators A: Phys.* 169 (2), 317–25 (2011).
9. HJ. Song, YT. Choi, NM. Wereley, A. Purekar. "Comparison of monolithic and composite piezoelectric material-based energy harvesting devices." *Journal of intelligent material systems and structures* 1-13 (2014).
10. SR. Anton, A. Erturk, DJ. Inman. "An Investigation on Multifunctional Piezoelectric Composite Spars for Energy Harvesting in Unmanned Aerial Vehicles." *Proceedings of the 17th International Conference on Composite* (2009).
11. SR. Anton, DJ. Inman. "Energy harvesting for unmanned aerial vehicles." In: *Proceeding of SPIE* (2008).
12. SR. Anton, A. Erturk, DJ. Inman. "Multifunctional Unmanned Aerial Vehicle Wing Spar for Low-Power Generation and Storage." *AIAA Journal of Aircraft* **49**, 292-301 (2012).
13. SR. Anton. "Multifunctional piezoelectric energy harvesting concepts." PhD Dissertation, Virginia Polytechnic Institute and State University (2011).
14. Y. Yang, L. Tang, H. Li. "Vibration energy harvesting using macro-fibre composites. *Smart Mater.*" *Struct* 18, 115025 (2009).

15. O. Bilgen, Y. Wang, DJ. Inman. "Electromechanical comparison of cantilevered beams with multifunctional piezoceramic devices." *Mechanical Systems and signal processing* 27, 763-77 (2014).
16. Z. Wang, W. Wu. "Nanotechnology-enabled energy harvesting for self-powered micro-/nanosystems." *Angewandte chemie international edition* 51(47), 11700-21 (2012).
17. HA. Sodano. "Macro-fibre composites for sensing, actuation and power generation." Master thesis. Virginia polytechnic institute and state university (2003).
18. WK. Wilkie, GR. Bryant, JW. High. "NASA-Langley Research Center Macro-Fiber Composite Actuator (LaRC-MFC): Technical Overview."
19. BR. Williams, BW. Grimsley, DJ. Inman, WK. Wilkie. "Manufacturing and Mechanics-Based Characterization of Macro Fiber Composite Actuators." *Proceedings of the ASME International Mechanical Engineering Conference and Exposition, New Orleans, Louisiana, (2002).*
20. Smart material. <http://www.smart-material.com/MFC-product-main.html>
21. TP. Daue, JK. Kunzmann, A. Schönecker. "Energy harvesting systems using piezo-electric macro fibre composites." Fraunhofer IKTS and Smart Material Corp. joint publication.
22. A. Wildschek. "An adaptive feed-forward controller for active wing bending vibration alleviation on large transport aircraft." Munich, Germany: Verlag Dr. Hut (2009).
23. TL. Lomax. "Structural Loads Analysis for Commercial Transport Aircraft: Theory and Practice." Reston, VA: AIAA Education Series (1996).
24. FJ. Hawkings, RF. Mousley. "Resonance tests on a Beagle B206 series aircraft." Reports and memoranda. Aeronautical research council, London (1969).
25. JR. Wait, MD. Todd. "Validation of macro fibre composites as strain sensors." IMAC-XXV: conference & exposition on structural dynamics (2007).
26. F. Lu, HP. Lee, SP. Lim. "Modelling and analysis of micro piezoelectric power generators for micro-electromechanical-systems applications." *Smart materials and structures* 13, 57-63 (2004).

27. MA. Trinadade, A. Benjeddou. "Characterisation of electric field dependence of d31piezoelectric Macro Fibre Composites effective properties." 6th ECCOMAS Conference on Smart Structures and Materials, Turin (2013).
28. L. Tang, Y. Yang, H. Li. "Optimizing efficiency of energy harvesting by macro-fiber composites." Proceedings paper 7268,1-9 (2008).

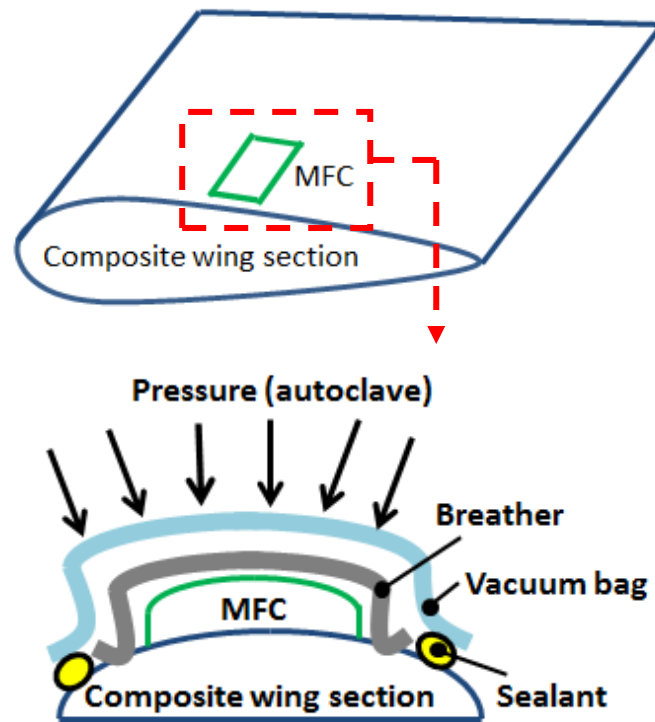


Fig. 1 Vacuum bag for integration MFC onto curved airframe.

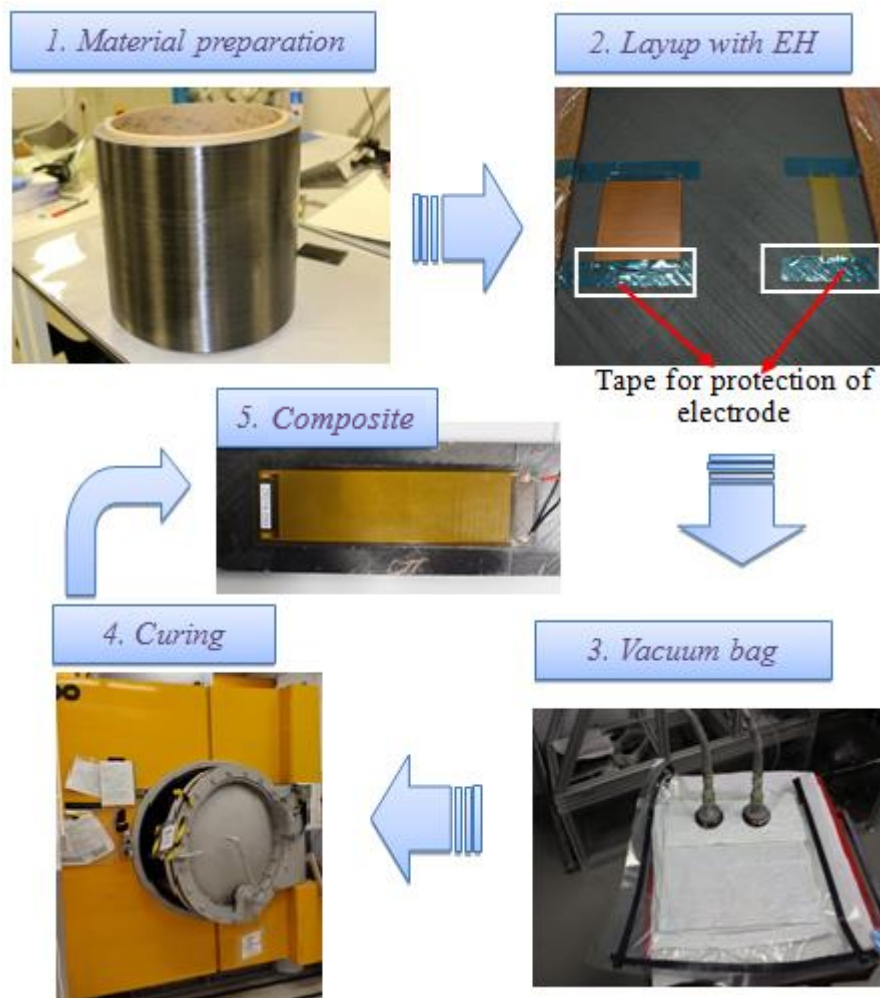


Fig. 2 Demonstration of co-curing process for integration of energy harvesting elements.

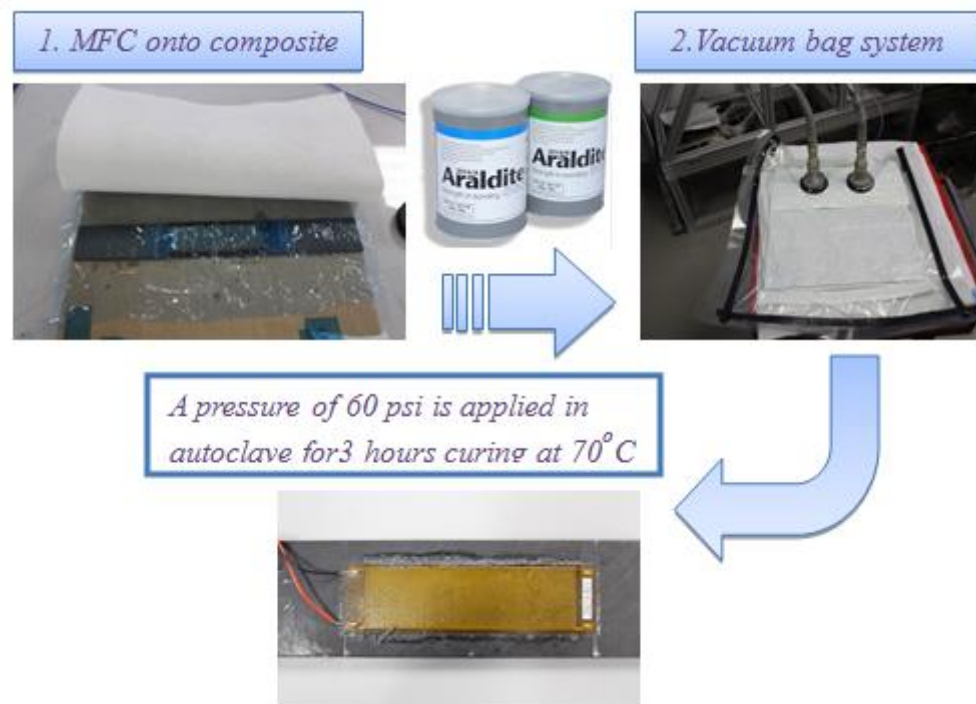


Fig. 3 Demonstration of directly bonding process by vacuum bag method

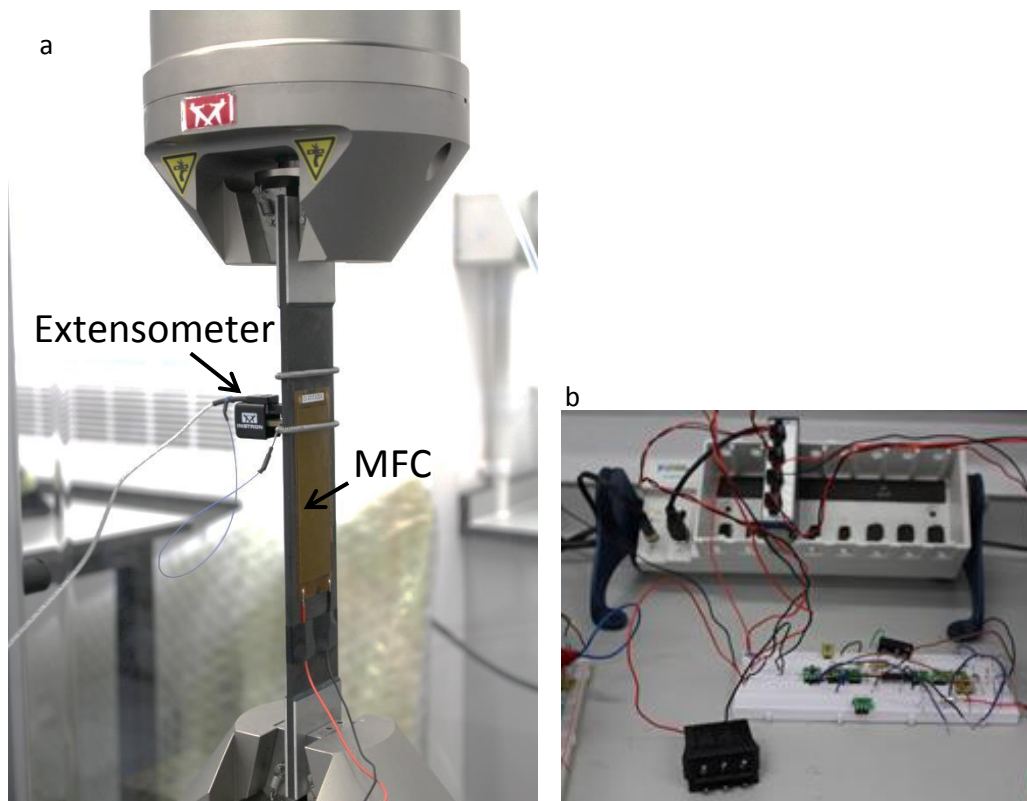
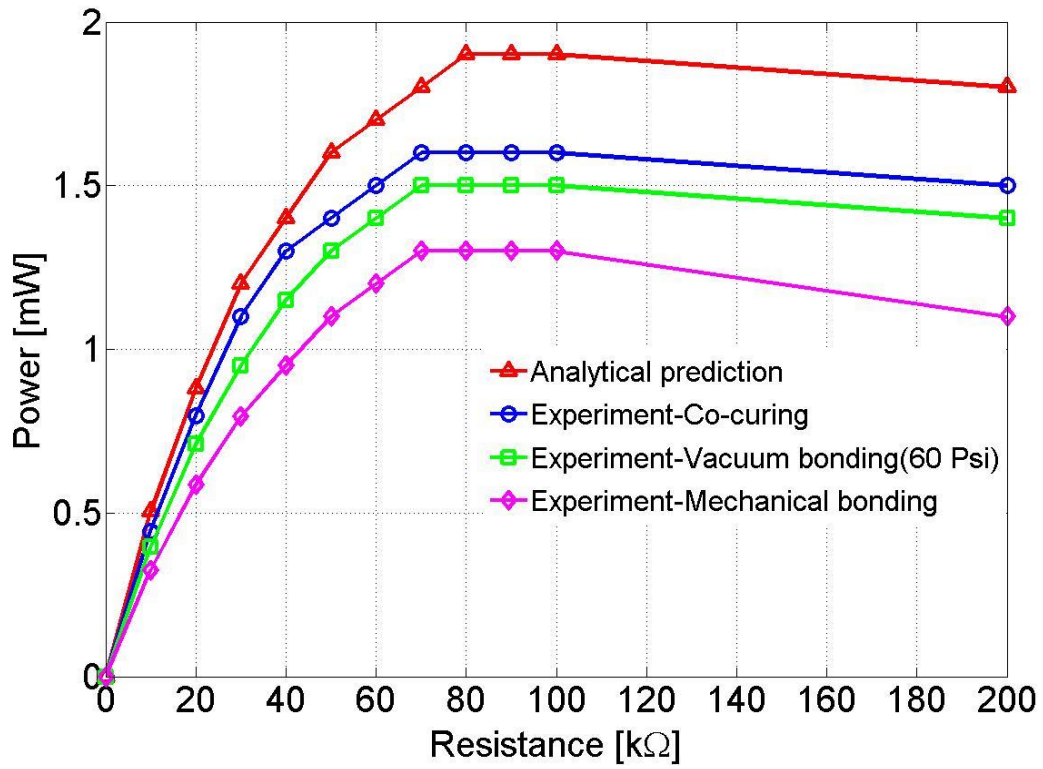
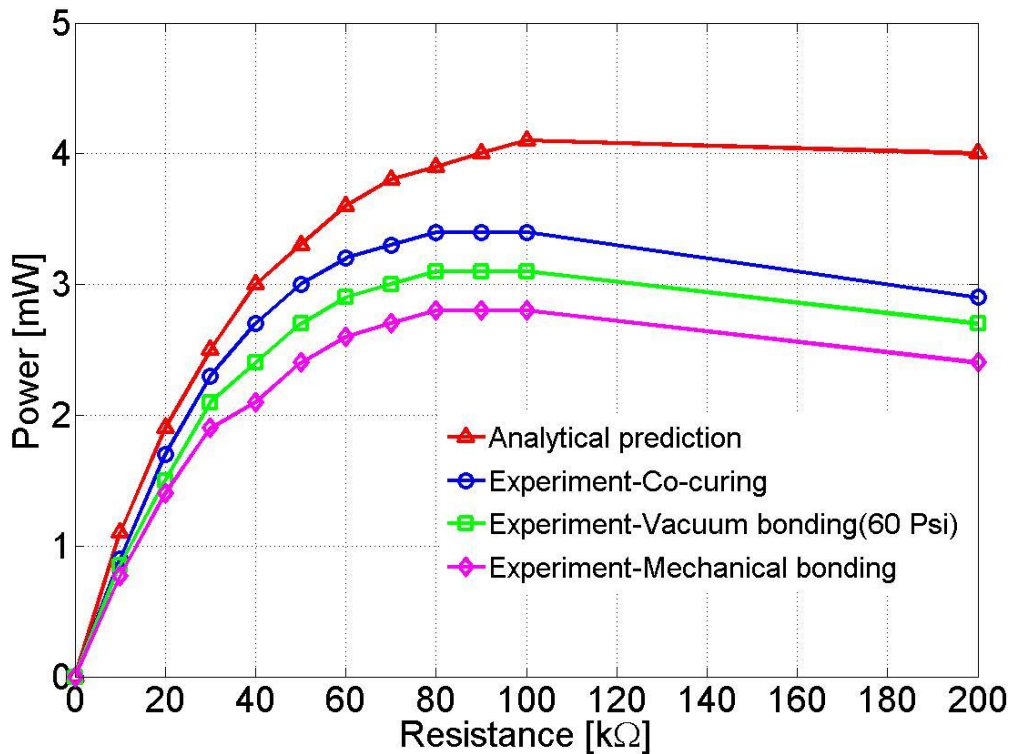


Fig. 4 Experiment set-up a) Composite substrate with MFC and extensometer mounted. b) electric system with external resistor for measurement of voltage and power.

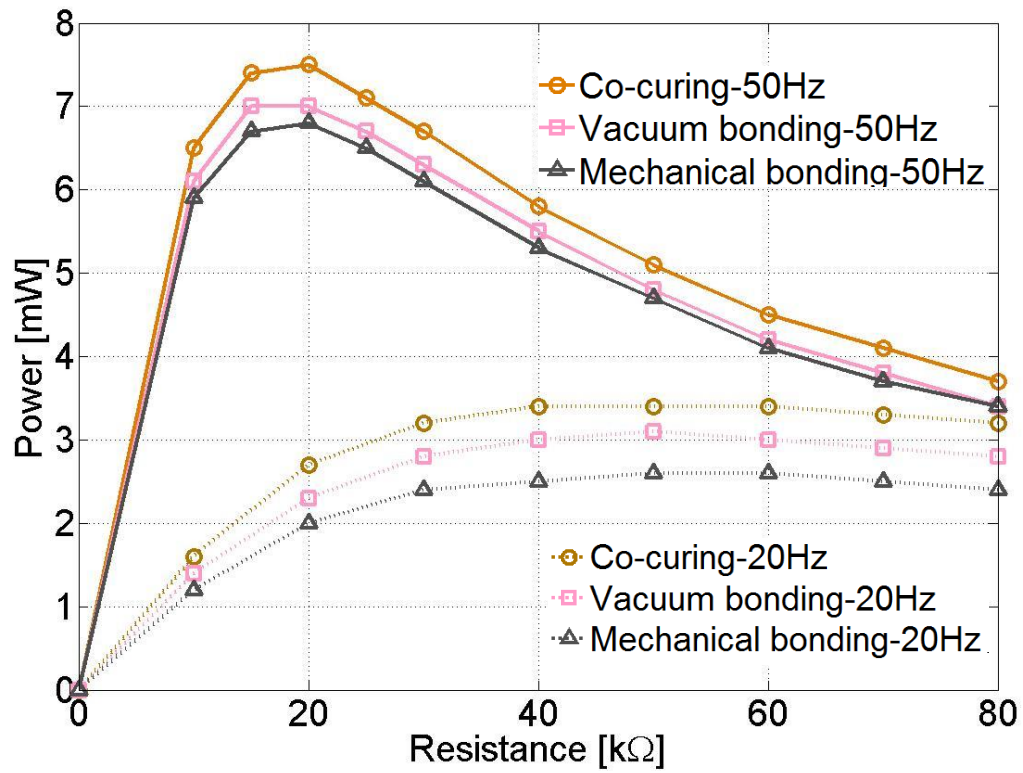


a. Peak-to-peak strain of 340με

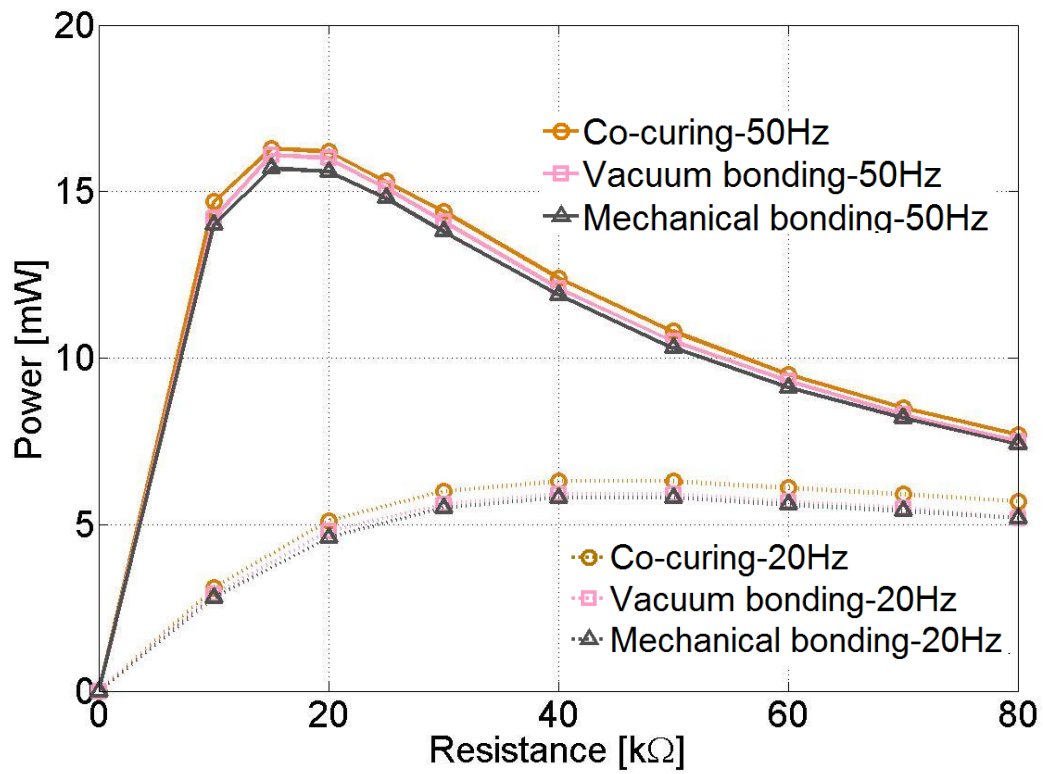


b. Peak-to-peak strain of 500με

Fig. 5 Power harvested vs resistance at 10 Hz a) peak-to-peak strain of 340με b) peak-to-peak strain of 500με.



a. Peak-to-peak strain of 340 $\mu\epsilon$



b. Peak-to-peak strain of 500 $\mu\epsilon$

Fig. 6 Power harvested as a function of resistance for different excitation frequencies and strain levels a) peak-to-peak strain of 340 $\mu\epsilon$ b) peak-to-peak strain of 500 $\mu\epsilon$.

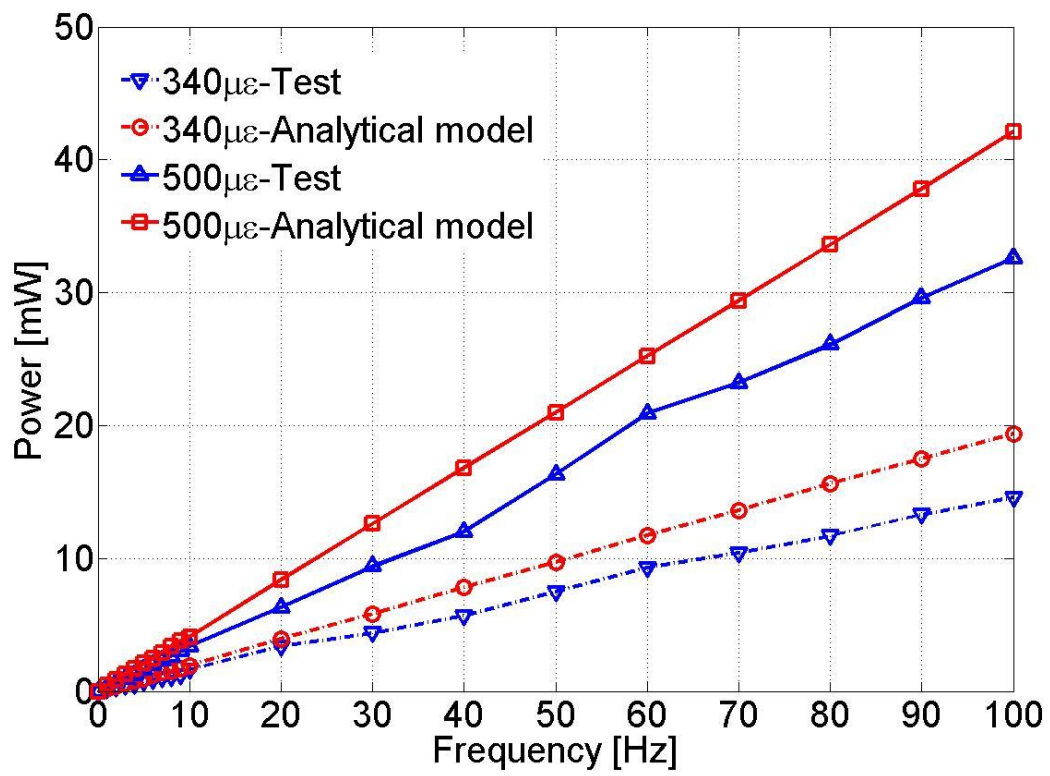


Fig.7 Experimental and analytical maximum power harvested at frequency sweep tests ranged from 1 to 100 Hz.

Table 1. MFC properties [20,26-27]

Material Property	M8525-P2 [20]
Mechanical properties	
Young's Modulus, E (GPa)	
Y^*	31.4 [26]
Y^{**}	15.86
Shear Modulus, G (GPa)	
G_{12}	5.52
Possion's Ratio, ν	
ν_{12}	0.31
Piezoelectric properties	
Piezoelectric constants (C/N)	
d_{31}	1.87E-10 [27]
d_{33}	4E-10
Dielectric Permittivity, ϵ (F/M)	
ϵ_{33}	1.5E-8[27]

* indicate the rod direction

** electrode direction

Table 2. Power harvested for different integration methods of MFC

Strain _{p-p} (μϵ)	340			500		
Frequency (Hz)	Power [mW]					
	Co-curing	60psi	Mechanical bonding	Co-curing	60psi	Mechanical bonding
10	1.6	1.5	1.3	3.4	3.1	2.8
20	3.4	3	2.6	6.3	5.9	5.8
30	4.4	4.1	3.9	9.4	9.1	8.6
40	5.7	5.4	5.3	12	11.8	11.7
50	7.5	7	6.8	16.3	16.1	15.7

Table 3. Power harvested for co-curing at frequencies between 1-100Hz

Frequency [Hz]	340 $\mu\epsilon$			500 $\mu\epsilon$		
	Electrical load[k Ω]	Power [mW]	Analytical calculation[mW]	Electrical load[k Ω]	Power [mW]	Analytical calculation[mW]
1	1300	0.158	0.195	1300	0.339	0.42
2	670	0.33	0.389	660	0.63	0.84
3	440	0.45	0.583	430	0.944	1.3
4	250	0.55	0.77	220	1.2	1.7
5	220	0.75	0.97	200	1.6	2.1
6	180	0.9	1.2	160	2	2.5
7	140	1	1.4	140	2.3	2.9
8	110	1.1	1.5	110	2.6	3.4
9	100	1.2	1.7	100	3	3.8
10	86	1.6	1.9	91	3.4	4.1
20	55	3.4	3.9	57	6.3	8.4
30	36	4.4	5.8	39	9.4	12.6
40	30	5.7	7.8	30	12	16.8
50	23	7.5	9.7	25	16.3	21
60	21	9.3	11.7	20	20.9	25.2
70	17	10.4	13.6	18	23.2	29.4
80	16	11.7	15.6	15	26.1	33.6
90	14	13.3	17.5	14	29.6	37.8
100	12	14.6	19.4	13	32.6	42.1